

Integrated Dry NO_x/SO₂ Emissions Control System Performance Summary

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ABSTRACT

The Integrated Dry NO_x/SO₂ Emissions Control System was installed at Public Service Company of Colorado's Arapahoe 4 generating station in 1992 in cooperation with the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI). This full-scale 100 MWe demonstration combines low-NO_x burners, overfire air, and selective non-catalytic reduction (SNCR) for NO_x control and dry sorbent injection (DSI) with or without humidification for SO₂ control. Operation and testing of the Integrated Dry NO_x/SO₂ Emissions Control System began in August 1992 and will continue through 1996. Results of the NO_x control technologies show that the original system goal of 70% NO_x removal has been easily met and the combustion and SNCR systems can achieve NO_x removals of up to 80% at full load. Duct injection of commercial calcium hydroxide has achieved a maximum SO₂ removal of nearly 40% while humidifying the flue gas to a 20°F approach to saturation. Sodium-based dry sorbent injection has provided SO₂ removal of over 70% without the occurrence of a visible NO₂ plume. Recent test work has improved SNCR performance at low loads and has demonstrated that combined dry sodium injection and SNCR yields both lower NO₂ levels and NH₃ slip than either technology alone.

INTRODUCTION

Public Service Company of Colorado (PSCC) was selected by DOE for a CTT-III project in December 1989 to demonstrate an Integrated Dry NO_x/SO₂ Emissions Control System. The demonstration project is taking place at PSCC's Arapahoe Unit 4, a 100 MWe top-fired unit

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which fires a low sulfur (0.4%) Colorado bituminous coal as its main fuel, but also has 100% natural gas capability. Figure 1 shows a boiler elevation drawing.

The Integrated Dry NO_x/SO₂ Emissions Control System combines five major control technologies to form an integrated system to control both NO_x and SO₂ emissions. The system uses low-NO_x burners, overfire air, and urea injection to reduce NO_x emissions, and dry sorbent injection using either sodium- or calcium-based reagents with (or without) humidification to control SO₂ emissions. The goal of the project was to reduce NO_x and SO₂ emissions by up to 70%. The combustion modifications were expected to reduce NO_x by 50%, and the SNCR system was expected to increase the total NO_x reduction to 70%. Dry Sorbent Injection was expected to provide 50% removal of the SO₂ emissions while using calcium-based reagents. Because sodium is much more reactive than calcium, it was expected to provide SO₂ removals of up to 70%. Figure 2 shows a simplified schematic of the Integrated Dry NO_x/SO₂ Emissions Control System at Arapahoe Unit 4.

The total cost of this innovative demonstration project is estimated to be \$27,411,000. Funding is being provided by DOE (50%), PSCC (43.7%), and EPRI (6.3%). DOE funding is being provided as a zero interest loan and is expected to be paid back from the proceeds obtained during commercialization of the technology over a 20-year period which begins at the conclusion of the demonstration project.

Construction began in July 1991 and was completed in August 1992. The test program began in August 1992 and all low sulfur coal testing was scheduled for completion in June 1994. Addition of the new SNCR injection location and alternate lance design tests will extend the test program through December 1996. Project completion is currently scheduled for February 1997.

Prior publications presented results of the performance of the individual technologies (1-11). This paper will provide a brief overview of the individual technologies and their performance, but will focus on results from recent test activities. These recent activities have included: 1) testing of a new SNCR injection location to improve low load performance; 2) long term performance of the integrated system; and 3) recent results of ammonia adsorption in the ash.

TECHNOLOGY DESCRIPTION

This section will provide a brief description of the technologies used in the integrated NO_x/SO₂ Emissions Control System with emphasis on the SNCR and sodium dry sorbent injection system. The reader is referred to prior publications for more complete descriptions of the low NO_x combustion system and calcium dry sorbent system with humidification.⁽¹⁻¹¹⁾

Low NO_x Combustion System

B&W's DRB-XCL® (Dual Register Burner-axially Controlled Low-NO_x) burner had been successfully used to reduce NO_x emissions on wall-fired boilers but had never been used in a vertically-fired furnace. The burner utilizes dual registers to control near burner mixing and a sliding air damper to control air flow to each individual burner independent of swirl. Twelve of these burners were installed on the roof of Arapahoe Unit 4. The low NO_x combustion system

also incorporated three B&W dual zone NO_x ports which were added to each side of the furnace approximately 20 feet below the boiler roof. These ports can inject up to 28% of the total combustion air through the furnace sidewalls.

Arapahoe Unit 4 was originally designed with the ability to fire 100% natural gas. Natural gas firing capabilities were maintained with the DRB-XCL® burners by installing a gas ring header at the tip of the burner. However, the burner is not specifically designed to be a low-NO_x burner with natural gas firing.

Selective Non-Catalytic Reduction

The purpose of the SNCR system at Arapahoe was two-fold. First, to further reduce the final NO_x emissions obtained with the combustion modification so that the goal of 70% NO_x removal could be achieved. Second, the SNCR system is an important part of the integrated system interacting synergistically with the dry sodium injection system. During this program, it was shown that when both systems are used simultaneously, both NO₂ emissions from the sodium system and NH₃ slip from the SNCR system are reduced.

When the SNCR system was originally designed and installed, it incorporated two levels of wall injectors with 10 injectors at each level. These two separate levels were intended to provide load following capability. The locations of these two levels were based on flue gas temperature measurements made with the original combustion system. However, the retrofit low-NO_x combustion system resulted in a decrease in the furnace exit gas temperature of nominally 200°F. This decrease in temperature moved the cooler injection level out of the SNCR temperature window. With only one operational injection level, the load-following performance of the system was compromised.

Two approaches were pursued to improve the low load performance of the SNCR system. First, short-term testing showed ammonia to be more effective than urea at low loads. Although ammonia was more effective than urea, it remained desirable to store urea due to safety concerns. A system was installed that allows on-line conversion of urea into ammonia compounds. The on-line conversion system improved low load performance, but the improvement was not as large as desired at the lowest load (60 MWe).

More recently, NOELL, Inc. (the original supplier of the SNCR system) suggested an additional injection location in a higher temperature region of the furnace. Because no unit outages were planned, the only option for incorporating an additional injection level was to utilize two existing (but unused) sootblower ports in conjunction with NOELL's Advanced Retractable Injection Lances (ARILs). This location was chosen because the ports existed, not because the temperatures were ideal for SNCR.

Figure 3 shows a diagram of the SNCR system installed at Arapahoe Unit 4. The system uses NOELL's proprietary dual-fluid injection nozzles to distribute the urea uniformly into the boiler. A centrifugal compressor is used to supply a large volume of medium-pressure air to the injection nozzles. The large quantity of air helps to atomize the urea solution as well as provide energy to rapidly mix the atomized solution with the combustion products. The SNCR system includes the option of passing the urea solution over a proprietary catalyst which converts the urea to

ammonia-based compounds. This ammonia conversion system was not utilized during the current series of tests described in this paper.

Figure 4 shows the location of the new ARIL lances relative to the two original SNCR injection locations. Level 2 is the location that became unusable as a result of the flue gas temperature decrease after the low-NO_x combustion system retrofit. The ARIL system consists of two retractable lances and two retractable lance drive mechanisms. Each lance is nominally 4 inches in diameter and approximately 20 feet in length. Each lance has a single row of nine injection nozzles spaced on two-foot centers. A single division wall separates the Arapahoe Unit 4 furnace into east and west halves, each with a width of approximately 20 feet. When each lance is inserted, the first and last nozzles are nominally one foot away from the division and outside walls, respectively.

Each injection nozzle is composed of a fixed air orifice (nominally one-inch in diameter), and a replaceable liquid orifice. The liquid orifices are designed for easy removal and cleaning, because they can become plugged. This ability to change nozzles also allows adjustments in the chemical injection pattern along the length of the lance in order to compensate for any significant maldistributions of flue gas velocity, temperature, or baseline NO_x concentration.

Two separate internal liquid piping circuits are used to direct the chemical to the individual injection nozzles in each lance. The four nozzles near the tip of the lance are supplied by one circuit, and the remaining five are supplied by the other. This provides the ability to bias the chemical flow between the "inside" and "outside" halves of each side of the furnace in order to compensate for various coal mill out-of-service patterns. Each lance is also supplied with a pair of internal thermocouples for detecting inside metal temperatures at the tip of the lance.

The retractable lance drive mechanisms were supplied by Diamond Power Specialty Co. (DPSC). The drives are Model IK 525's which have been modified for the liquid and air supply parts. Both remote (automatic) and/or local (manual) insertion and retraction operations are accomplished with the standard IK electric motor and gearbox drive system. A local control panel is provided on each side of the boiler, attached to each ARIL lance drive mechanism. Each panel contains a programmable logic controller for the lance install/retract sequencing and safety interlocks. Each lance can be rotated either manually at the panel, or automatically by the control system during load-following operation. One of the key features of the ARIL lance system is its ability to rotate the lances. As will be discussed, this feature provides a high degree of flexibility in optimizing SNCR performance by varying the flue gas temperature at the injection location by simply rotating the lance.

In addition to NOELL's ARIL lances, an alternate lance design, supplied by Diamond Power Specialty Company, was also evaluated. This alternate lance design represented a simplification to the original ARIL design. The liquid solution is injected through a single pressure atomizer located in the air supply pipe ahead of the lance. This eliminates the internal liquid piping, and spraying at the lance inlet provides evaporative cooling to help cool the lance. In addition, the design prevents air and liquid from being injected in the local region around the boiler when the lances are retracted.

Dry Sorbent Injection

PSCC designed and installed a dry sorbent injection system that can inject either calcium- or sodium-based reagents into the flue gas upstream of the fabric filter. Figure 5 shows a simplified flow diagram of the equipment. The reagent is fed through a volumetric feeder into a pneumatic conveying system. The air and material then pass through a pulverizer where the material can be pulverized to approximately 90% passing 400 U.S. Standard mesh. The material is then conveyed to the duct and evenly injected into the flue gas. After the original results suggested that the duct flue gas temperature was too low for effective SO₂ removal with sodium bicarbonate, the dry injection system was modified to allow injection of sodium-based compounds at the entrance to the air heater where the flue gas temperature is approximately 600°F. The pulverizer can be bypassed allowing calcium hydroxide to be fed from the silos and injected either ahead of the fabric filter or into the boiler economizer region where the flue gas temperature is approximately 1000°F.

To improve SO₂ removal with calcium hydroxide, a humidification system capable of achieving a 20°F approach to saturation temperature has been installed. The system was designed by B&W and includes 84 I-Jet humidification nozzles which can inject up to 80 gpm of water into the flue gas ductwork. The humidifier is located approximately 100 feet ahead of the fabric filter and there is no bypass duct.

Balance of Plant

Besides the major environmental equipment, the project also included required upgrades to the existing plant. A new distributed control system was installed to control the boiler and other pollution control equipment added as part of the integrated system. The fly ash collection system was also converted from a wet to a dry collection system to allow dry collection of the ash and injection waste products. A Continuous Emissions Monitor (CEM) system was installed at Arapahoe Unit 4 to collect data for the extensive test program. This monitor allows measurements of N₂O, NH₃, NO₂, and H₂O in addition to the more common pollutants.

RESULTS

Fossil Energy Research Corporation (FERCo) of Laguna Hills, California, has been performing all testing of the Integrated Dry NO_x/SO₂ Emissions Control System. The test program is nearing completion and the individual testing of the low-NO_x burners, overfire air, urea injection, calcium duct injection, calcium economizer injection, and sodium injection has been completed. Testing of the SNCR lances and the complete integrated system while firing low-sulfur coal is in progress. In addition to efficiency and emissions measurements, four tests were conducted to determine baseline and removal capabilities of the system for many common air toxic emissions. Prior papers (1-11) also discussed the performance of the individual technologies. This paper will overview these prior results and focus on the performance of the new SNCR injection lances and the performance of the integrated system. In addition, the paper will also present some recent information on NH₃ absorption on fly ash and the impacts on fly ash handling.

Review of NO_x and SO₂ Reduction Performance

This section will provide a brief overview of the NO_x and SO₂ reductions from the individual technologies used in the integrated system. The reader is referred to prior publications for more detailed discussions (1-11).

Low-NO_x Combustion System Performance

The following section describes the performance of the low-NO_x combustion system (low-NO_x burners and OFA ports).

Low-NO_x Burners

Figure 6 compares the Arapahoe Unit 4's NO_x emissions before and after the retrofitting of the low-NO_x combustion system. Note, NO_x (NO + NO₂) and NO are used interchangeably when discussing the performance of the combustion system, since NO₂ levels are very low for this unit. The original combustion system produced nearly uniform NO_x emissions of 800 ppmc (corrected to 3% O₂, dry) or 1.1 lb/MMBtu across the boiler's load range. The low-NO_x combustion system reduced NO_x emissions by over 63 percent, to less than 300 ppmc, across the boiler's load range. Note that all testing was conducted under steady-state conditions and with the careful supervision of test technicians to achieve the maximum possible reduction in NO_x emissions. Under load following conditions, NO_x emissions were about 10 to 25% higher. Additional modifications to the control system and additional operator training may decrease the difference.

Overfire Air

At full load, opening the OFA control dampers to full open (maximum OFA) diverts about 24% of the total combustion air to the OFA ports and at low load (60 MWe) it diverts about 28% of the combustion air. At maximum OFA, the low-NO_x combustion system reduces NO_x emissions by 62 to 69% across the load range. Since the OFA ports are located in a very hot part of the boiler, a significant amount of cooling air is required and the minimum amount of OFA is limited to about 15% of the total combustion air at full load and about 8% at low load. At minimum OFA, the retrofitted combustion system reduces NO_x emissions by 60 to 63%. Arapahoe Unit 4 cannot be tested at 0% OFA, but the small difference in NO_x reduction between maximum and minimum OFA indicates that the low-NO_x burners are responsible for most of the NO_x reduction.

SNCR System Performance

As mentioned previously, in addition to reducing NO_x emissions significantly, the low-NO_x combustion system also reduced the temperature of flue gas at the furnace exit by about 200°F. Since SNCR systems are very sensitive to changes in flue-gas temperatures, this reduction made the flue-gas temperature too cold for one row of injection nozzles, so all testing was performed using the row of injection nozzles originally designed for loads below 80 MWe. Figure 7 shows the SNCR performance achievable over the load range for a 10 ppm NH₃ slip limit with this single

row of injectors. At full load, NO_x reductions of 45% are achieved. However, the performance decreased dramatically as the load decreased; at 60 MW, NO_x removals were limited to 11% for a 10 ppm NH₃ slip.

Calcium-Based Economizer Injection Performance

SO₂ removal has been less than expected with calcium hydroxide injection at the economizer. Initial testing at a Ca/S molar ratio of 2.0 without humidification resulted in SO₂ removals in the range of 5 to 8%. Note that the stoichiometric ratio for the Ca/SO₂ reaction is 1.0, since one mole of Ca reacts with one mole of SO₂ to form calcium sulfate, CaSO₄. It was found that the sorbent distribution was very poor, and only approximately one-third of the flue gas was being treated. New nozzles that increased reagent distribution only increased the SO₂ removal to 15% at a Ca/S molar ratio of 2.0. Although distribution of the calcium reagent is far from perfect, it appears that high levels of SO₂ removal are not possible at Arapahoe Unit 4 using the current Ca(OH)₂ material, even in areas with high Ca/S molar ratios.

Calcium-Based Duct Injection Performance

Higher SO₂ removal was achieved with duct injection of calcium hydroxide and humidification with SO₂ removals approaching 40% at Ca/S ratios of 2.0 and approach to saturation temperatures of 20 to 30°F. These levels of SO₂ removal are consistent with the prior DOE study at Ohio Edison's Edgewater Station.^[13] Immediately after this test, problems developed with the dry fly ash transport system, and it is suspected that the low approach temperature contributed to this problem. Then, after a short period of 24 hour/day testing during load following operation, fabric filter pressure drop significantly increased due to the buildup of a hard ash cake on the fabric filter bags which could not be cleaned during normal reverse air cleaning. The heavy ash cakes were caused by the humidification system, but it was not possible to determine if the problem was caused by operation at a 30°F approach temperature or a short-excursion to a lower approach temperature caused by a rapid decrease in boiler load.

Sodium-Based Injection

Sodium-based reagents are much more reactive than calcium-based sorbents and can achieve significantly higher SO₂ removals during dry injection.^[14,15] Figure 8 shows the SO₂ removal for dry sorbent injection for sodium bicarbonate and sodium sesquicarbonate. In Figure 8, SO₂ removals are plotted as a function of Normalized Stoichiometric Ratio (NSR). This corresponds to the amount of sodium compound injected relative to the amount of sodium required to form sodium sulfate, Na₂SO₄ (i.e., two moles of Na per mole SO₂). Sodium bicarbonate provided the highest SO₂ removal and was also the most efficient reagent in terms of sodium utilization. Flue gas temperature at the fabric filter inlet duct at Arapahoe Unit 4 varies from 250 to 280°F. The dry sorbent injection (DSI) system was originally designed for duct injection before the fabric filter only. However, initial testing with sodium bicarbonate showed that SO₂ removal was erratic, which was attributed to the low flue gas temperatures. The DSI system was modified to inject sodium sorbents at the air heater inlet where the flue gas temperature is approximately

600°F. It should be noted that sodium sesquicarbonate does not exhibit this slow reaction rate when injected ahead of the fabric filter.

A major disadvantage of sodium-based injection is that it converts some existing NO in the flue gas to NO₂. In addition, during the conversion process a small amount of the total NO_x, 5 to 15%, is removed. However, the net NO₂ exiting the stack is increased. While NO is a colorless gas, small quantities of the brown/orange NO₂ can cause a visible plume to develop. The chemistry of the conversion is not well understood but it is generally accepted that NO₂ increases as SO₂ removal increases. Figure 8 shows that NO₂ emissions are generally higher with sodium bicarbonate, although a significant amount of data scatter exists. The threshold NO₂ level that forms a visible plume is site specific; at Arapahoe Unit 4, a visible plume appears when NO₂ concentrations reach 30 to 35 ppm. Also, the NO₂ levels were found to depend on conditions in the fabric filter with NO₂ levels increasing dramatically after each cleaning cycle.⁽¹¹⁾

SNCR Lance Performance Results

The recent test work has focused on the performance of the SNCR lances, both the NOELL ARIL lances and a comparison of the performance of the alternate DPSC lance to the ARIL lance.

ARIL Lances

Prior to incorporating the ARIL lances into the SNCR control system, a series of parametric tests was conducted to define the optimum injection angle at each load. As shown in Figure 4, each lance can rotate to inject urea into a different region of the furnace in order to follow the SNCR temperature window as the boiler load changes. The minimum injection angle is 22° (0° corresponds to injection vertically downward), at which point the chemical is injected parallel to the tube wall located below the lances. Smaller injection angles are not used to avoid direct liquid impingement on these tubes. An injection angle of 90° corresponds to injection straight across the furnace toward the front wall, and an angle greater than 90° results in injection of the solution in a direction up toward the roof-mounted burners.

While the primary focus of the parametric tests was to define the injection angle versus load, the tests also investigated the effects of:

- coal mill out-of-service patterns
- coal mill biasing
- biasing the urea flow along the length of the lances
- independent adjustment of the injection angles for each lance

The results of these tests are described below.

Effect of Lance Angle

One of the primary attributes of the ARIL lance system is the inherent flexibility of accessing the optimum flue gas temperature location by simply rotating the lance. Figure 9 shows the effect of varying the lance injection angle at loads of 43 and 50 MWe. All of the tests shown in these figures were performed at a N/NO_x ratio of 1.0, with two mills in service. At 43 MWe, varying the injection angle had little effect on NO_x removal, and the maximum removal occurred at an angle of 35 degrees (Figure 9a). However, Figure 9a shows that the lance angle had a large effect on NH₃ slip; decreasing from 46 ppm at an angle of 22° to under 5 ppm at an angle of 135°. This overall behavior at 43 MWe suggests that, on average, injection is occurring just on the high side of the SNCR temperature window. In fact, the optimum temperature, in terms of NO_x removal, appears to correspond to an angle of 35°. However, since it is desirable to maintain the NH₃ slip less than 10 ppm, an injection angle of 90° is a more appropriate operating angle at this load.

At a slightly higher load of 50 MWe (Figure 9b), the effect of lance injection angle was markedly different. At this load, where the average flue gas temperatures were higher, injection angle had little effect on NH₃ slip. However, at the higher temperature, lance angle had a large effect on NO_x removal. The relative insensitivity of the NH₃ slip and large sensitivity of the NO_x removal to lance angle suggests that at 50 MWe, chemical injection is occurring far on the high side of the SNCR temperature window for injection angles ranging from 22° to 135°.

The results at 43 and 50 MWe shown in Figure 9 illustrate how varying lance angle can be used to optimize the SNCR performance over the load range. As the load increases, the preferred injection angle will decrease. Again, the minimum angle is 22°, where the chemical is injected parallel to the tube sheet located below the lances.

Performance over the Load Range

The SNCR performance using the ARIL lances over the load range from 43 to 80 MWe is shown in Figure 10. Note that for this particular lance location, the flue gas temperatures are too high for the lances to be effective at loads greater than 80 MWe. As the load increases, the preferred lance angle decreases in order to inject the urea into a lower temperature region.

As discussed above, at 43 MWe with an angle of 90°, injection occurred on average just on the high temperature side of the window. At N/NO_x = 1, NO_x removals were 35% with less than 10 ppm NH₃ slip. At 50 MWe, a 45° injection angle was on average at a better location in the SNCR window, with NO_x removals of 40% and NH₃ slip less of 5 ppm at N/NO_x = 1. As the load increased to 60 MWe, a decrease in lance angle to 34° resulted in SNCR performance similar to a load of 43 MWe. At higher loads of 70 and 80 MWe, injection was clearly occurring on the high side of the temperature window. Note that the NH₃ slip at 80 MWe was higher than the slip at 70 MWe even though the chemical was injected into a region of higher overall temperature (i.e., compare the NO_x removals at 70 and 80 MWe in Figure 10). This effect was a result of temperature stratification in the furnace, and the way in which the stratification varies with different coal mill patterns. This effect is discussed in more detail below. However, comparing Figures 9 and 10 to the low load performance of the wall injectors in Figure 7 clearly shows that the lances have markedly improved the low-load performance of the SNCR system.

Effect of Boiler Operation on SNCR Performance

As mentioned above, local changes in temperature due to variations in boiler operating parameters (excess O₂, mill pattern, mill biases, etc.) can have a major impact on SNCR performance. This is particularly true at Arapahoe Unit 4 where the 12 burners are located on the roof of the furnace. Each of the four coal mills feeds three burners, two burners on one side of the furnace and a single burner on the other side of the furnace. Since the furnace has a division wall, there is an imbalance in heat release across the furnace, and a corresponding variation in flue gas temperature, when only three mills are in service. These temperature variations impact the performance of both the wall injectors and the ARIL lances. In this paper, the effect will be illustrated by looking at the performance of the ARIL lances with varying mill out-of-service patterns. During normal operation, Arapahoe Unit 4 operates with four mills in service over the load range from 80 to 110 MWe (although the unit can operate up to 100 MWe with only 3 mills). From 60 to 80 MWe, the unit typically operates with three mills in service. Below 60 MWe, the unit is usually operated with only two mills in service.

Figure 11 shows the effect of various mill out-of-service (OOS) patterns on east/west imbalances across the furnace. The bottom of Figure 11 shows a plan view of the in-service burners (numbered) and out-of-service burners (filled circles) for a given mill pattern. Note that the left side of these figures corresponds to the west wall of the furnace (adjacent to burners 1, 2 and 3), and the right side corresponds to the east wall (adjacent to burners 10, 11 and 12). With either A mill or C mill out-of-service, more heat release occurs on the east side of the furnace, while the west side has more heat release with either B mill or D mill out-of-service.

The change in lance metal temperatures provides a general indication of changes in flue gas temperatures on the east and west sides of the furnace. As seen in Figure 11, the changes in lance metal temperatures reflect the variations in heat release in the furnace with differing mill out-of-service patterns. Correspondingly, the NO_x removals and NH₃ slip levels also reflect these variations in temperature. For instance, NH₃ slip decreased on the west side when D mill was out-of-service, since more coal was fired (and the flue gas temperatures were higher) on the west side. The lance metal temperatures also indicated that, in general, the east side of the furnace was hotter than the west side. Figure 12 shows the overall impact of various mill out-of-service patterns on SNCR performance at 60 MWe. As can be seen, NO_x removals varied from 30% to 52% (@ N/NO_x = 1.5) depending on which particular mill was out-of-service. Comparably, the NH₃ slip varied from under 5 ppm to over 30 ppm with different mill-in-service patterns. This behavior made overall optimization of the SNCR system quite challenging.

In addition to the temperature variations that occur with the various mill out-of-service patterns, day-to-day variations can occur as a result of changes in the performance of the individual mills, or changes in any other variables which affect the flue gas temperature distribution. Three operational changes were investigated to deal with these types of temperature variations.

- varying the urea flow along the length of each lance
- independently varying each lance angle
- biasing the in-service coal mills

Varying the urea flow between the two liquid zones in each lance provided minor improvements in the performance of the SNCR system. Independently varying the lance angles as a function of

the mill-in-service pattern also provided minor improvements. Unfortunately the implementation of either of these strategies would significantly complicate the automatic control system. On the other hand, biasing the in-service coal mills, which is relatively easy to implement, resulted in major improvements in the performance of the SNCR system. Arapahoe Unit 4 is equipped with four O₂ monitors at the economizer exit. Biasing the coal mills to provide a balanced O₂ distribution at this location is a fairly simple exercise for the boiler control operator. Figure 13 shows the improvements in SNCR performance that can be achieved by biasing the coal mills. These tests were performed at a load of 60 MWe with both lances at an injection angle of 22° and A mill out-of-service. The “biased” condition in Figure 13 corresponds to a negative 10% bias on B mill and D mill, and a positive 10% bias on C mill. This has the net effect of moving coal from the east side to the west side of the furnace to compensate for A mill being out-of-service (see bottom of Figure 11). Biasing the mills increased NO_x removals from nominally 27% to 42% at an NH₃ slip limit of 10 ppm.

Overall System Performance

The parametric tests were conducted to determine at which loads the ARIL lances should be used, as well as the optimum injection angle for each of these loads. Based on the parametric tests, the control system has been set up to operate with the Level 1 wall injectors at loads above 80 MWe. Below 80 MWe, the ARIL lances are used. Figure 14 compares the NO_x removal over the load range for injection at the two locations with an NH₃ slip limit of 10 ppm. It is evident that the installation of the ARIL lances has improved low-load performance of the SNCR system. Currently, NO_x removals of more than 30% are achievable over the load range with less than 10 ppm NH₃ slip. The minimum NO_x removal of 30% occurs at 80 MWe, which corresponds to the point where the temperature becomes too high for the ARIL lances and too low for the Level 1 injectors. With continuing operation of the system, it is anticipated that further optimization will take place as the operators gain more experience balancing the furnace.

Alternate Lance Design

While the NO_x removal performance of the ARIL lances has been good, their location in the furnace has resulted in some operational problems. At this particular location in the furnace, the lances are exposed to a large differential heating between the top and bottom surfaces. The top surface receives a high radiant load from the burners, while the bottom of the lance radiantly communicates with the relatively cold tube wall immediately below. This uneven heating pattern causes a great amount of thermal expansion along the upper surface, and the lances bend downward toward the tubes. Within 30 minutes of insertion, the tip of each lance would drop by approximately 12 to 18 inches. Within less than six weeks of operation, the lances became permanently bent, making insertion and retraction difficult. This was partially addressed by adding additional cooling slots at the end of the lance.

An alternate lance design supplied by Diamond Power Specialty Company (DPSC) was evaluated during this test period. As mentioned previously, this design sprays the urea solution through a single atomizer at the entrance to the lance. This provides evaporative cooling to supplement the air cooling. The evaporative cooling was expected to help minimize the lance bending discussed above. This alternate lance design was evaluated by installing a single lance on the west side of

the boiler in place of one of NOELL's ARIL lances. The two different lance designs were compared during a nominal three week test program.

Overall, the DPSC lance performed mechanically well. The lance exhibited less bending than the ARIL lance, and eliminated air injection on the outside of the boiler.

Figure 15 compares the performance of the ARIL and DPSC lances on the west side of the furnace. In terms of NO_x reduction and NH_3 slip performance, the DPSC lance was not quite as good as the ARIL lance. With the B mill OOS, the ARIL lance yielded 42 percent NO_x removal with less than 5 ppm slip on the west side (60 MWe, $\text{N}/\text{NO}_x = 1$). Under comparable conditions, the DPSC lance yielded 36 percent NO_x removal and less than 5 ppm slip. This slight difference in performance is primarily attributable to the urea distribution along the lance. The ARIL lance uses a separate liquid circuit with individual liquid orifices at each air nozzle. This results in a fairly uniform liquid distribution along the length of the lance. The DPSC lance, on the other hand, sprays the urea solution into the cooling air stream at the inlet to the lance. Impingement on the walls and incomplete evaporation results in the liquid tending to be carried toward the far end of the lance, with part of the urea exiting as a stream of liquid rather than a finely atomized spray. In fact, this explains why the optimum angle for the DPSC lance is 34° compared to 22° for the ARIL lance at 60 MWe. The higher temperature associated with the 34° angle is needed to evaporate the liquid stream. In addition, the feed tube geometry of the DPSC lance created an additional pressure drop, restricting the amount of cooling air flow. This resulted in less penetration of the air jets, although this was partially compensated for by the unatomized portion of the urea solution, which carried the urea farther into the furnace before decomposing and releasing the reactive nitrogen components.

Overall, the results of the short test program of the DPSC lance were sufficiently positive that a second DPSC lance has been ordered. An additional three weeks of testing is planned.

Integrated System Performance

An important part of the test program was demonstrating the integrated performance of the various NO_x reduction and SO_2 removal technologies. In particular, a key element of the program was documenting the synergistic benefits of simultaneous operation of the SNCR and sodium-based dry sorbent injection system. When operated together, it was expected that the SNCR system would reduce NO_2 emissions from the sodium DSI system, while the sodium DSI system would in turn reduce NH_3 slip from the SNCR system.

Ideally, it would have been desirable to parametrically evaluate the merits of the integrated system over a range of operating conditions. This was not entirely possible for a number of reasons. With sodium-based dry sorbent injection, NO_2 levels are not only dependent on the amount of sodium injected, but also depend on the particulate in the fabric filter and the cleaning intervals.⁽¹¹⁾ Likewise, the time required for NH_3 levels to stabilize at the exit of the fabric filter, both before and after sodium injection, was greater than the 10-hour a day period during which the load from Arapahoe 4 could be blocked. Thus, characterizing the integrated performance relied on a limited number of parametric tests followed by a series of "long term" tests under normal load following conditions. During these "long-term" tests, the NO_x reduction and SO_2 removal systems were operated in automatic while the unit was operated according to system dispatch requirements.

Data were collected at regular intervals using a data logger. No effort was made to set up specific test conditions, as these tests were designed to simulate operation of these systems once they are turned over to the plant at the completion of this program.

The results of a parametric test with sodium sesquicarbonate injection and the SNCR system are shown in Figure 16. During these tests, the DSI system was started first, followed by the SNCR system. For this test, the DSI system was set at an NSR of 2.0 (i.e., 4 moles of sodium per mole of SO_2) and the SNCR system at $\text{N}/\text{NO}_x = 0.6$. Following the start of the DSI system, the SO_2 removal stabilizes at nominally 70% removal and the NO_x removal at 12%. This level of NO_x removal is consistent with previous tests of the DSI system. The NO_2 levels increased to only about three ppm at the point that the SNCR system was started. With the SNCR system started, the NO_x removal increased to 35 to 40% and the NO_2 levels remained constant at three ppm. Even following a cleaning cycle, the NO_2 levels did not increase with the SNCR system in operation. Just before 1800 hours, the SNCR system was turned off and an immediate increase in NO_2 was noted.

Figure 17 shows the results of a parametric test with sodium bicarbonate injection ahead of the air preheater. With sodium bicarbonate injection alone at an NSR of 1.1, NO_2 levels on the order of 50 ppm are expected (see Figure 8). For the test results shown in Figure 16, the SNCR system was started at $\text{N}/\text{NO} = 1.1$ nominally two hours before the DSI system. As can be seen, the NO_2 levels remained near zero for the entire test. Further, it can be seen that following the start of the DSI system, the NH_3 slip levels continued to decrease.

The results shown in Figures 16 and 17 clearly show that there is a synergistic benefit of operating the SNCR and sodium-based DSI systems simultaneously.

Because of the difficulties encountered running these short term integrated tests, the balance of the integrated tests were run under normal load following conditions. During these tests the integrated system was operated 24 hours per day. Figure 18 shows the data collected during one 24-hour period (February 25, 1996). During these tests, the integrated system was utilizing sodium sesquicarbonate injection ahead of the fabric filter, and the SNCR system was load following with both the wall injectors and ARIL lances.

On this day, the boiler load was nearly constant for the first 17 hours of the day. The N/NO_x ratio and NH_3 emissions were also relatively steady during this time. At 1600 hours, the DSI system was started with a 75 percent SO_2 removal setpoint with the hope that the load would remain steady and it would be possible to assess the beneficial effects of running the integrated system. Although, the load increased significantly about two hours after the DSI system was started, it eventually settled back down to a level similar to the level before the increase. Figure 18 shows that the average NH_3 emissions with and without sodium injection were similar, which was expected since the NH_3 trim control was functioning during both of these tests. However, the results also show that there was a substantial increase in the N/NO_x ratio. Since the SNCR control system was set to maintain the NH_3 emissions within the range of 7 to 8 ppm, it should have increased the urea injection rate if the DSI system reduced NH_3 emissions. A temporary increase was expected as a result of the load swing, but the N/NO_x ratio should have returned to the pre-swing level within two to three hours (as was seen after the "morning demand peak" between 0800 and 0900 hours). When the DSI system was started at 1600 hours, there was an immediate 10 percent increase in the NO_x removal, which is consistent with the increases seen

during sodium-based DSI-only tests. After this initial NO_x removal increase, there was another slower increase (amounting to nominally 10 to 15 percent removal) which occurred as the N/NO_x ratio increased. Although the scaling of the data makes it difficult to see, Figure 18 indicates that the N/NO_x ratio basically doubled after the DSI system was started. The increase in N_2O emissions (from nominally 8 to 16 ppm), confirms that the N/NO_x ratio was increased by roughly a factor of two. These results clearly indicate that there was a substantial reduction in the stack NH_3 slip, when the SNCR and DSI systems were run concurrently.

Figure 19 shows data collected during the 24-hour period on March 4, 1996. The DSI system was operated for the entire period and the SNCR system was started at 1420 hours. The boiler load was fairly steady at this time, and was low enough for the control system to insert the ARIL lances. Although the DSI feedrate was not very consistent, Figure 18 shows that there was nominally a 50 percent reduction in the NO_2 emissions when urea injection began. The load remained steady for nearly four hours; then it increased for the usual “evening demand peak” at 1800 hours. When the lances retracted, the N/NO_x ratio dropped as demanded by the control system, and the NO_2 emissions were also seen to decrease. By 1900 hours, the NO_2 emissions had been reduced to near-zero levels. This effect is due to the difference in the NH_3 emissions between injection at the Level 1 and ARIL locations. Although effort was made to set up the SNCR control system such that the NH_3 slip was limited to 10 ppm throughout the load range, the Level 1 location is “cooler” overall than the ARIL location; thus injection at Level 1 is more sensitive to variations in the flue gas temperature profile. Therefore, in general, urea injection at the Level 1 location results in higher NH_3 slip levels at the fabric filter inlet. Since the NH_3 emissions are generally higher with urea injection at the Level 1 location, it would be expected that the reduction in stack NO_2 emissions would also be higher (relative to injection at the ARIL location). The hypothesis is further supported by the decrease in NO_2 emissions seen when the urea injection switched from the lances to Level 1 at 1800 hours in Figure 19, but also by the increase in NO_2 seen when the lances were reinserted at 2000 hours. When the lances went in at this time, the NO_2 emissions were essentially zero. After an hour, however, the NO_2 emissions slowly began to increase, finally leveling out at approximately 8 ppm.

The above (Figures 16 through 19) demonstrate the synergistic benefits of the integrated process. The NH_3 slip from the SNCR process suppresses the NO_2 emissions associated with NO to NO_2 oxidation by dry sodium injection. Concurrently, the sodium reduces the NH_3 slip from the SNCR process. (Note: In the present case, the control system adjusts the urea injection rate to maintain a set NH_3 slip level, and the tendency to reduce NH_3 slip is manifested in a higher N/NO_x ratio for a given NH_3 slip.)

Ammonia Absorption on the Fly Ash

An issue that needs to be addressed with any post-combustion NO_x reduction technology with NH_3 slip is the absorption of ammonia on the fly ash. This can have a number of impacts ranging from personnel safety while handling the ash, odor problems, or impacting the salability of the ash for future use as a cement aggregate. In the latter, a salable product becomes a disposal problem with an attached economic penalty. At the Arapahoe Station, the ash is not sold for use in cement. Thus, the only problems that have been encountered have been an occasional NH_3 odor around the ash handling area and potential concern with worker safety should the concentrations become too high.

At Arapahoe Unit 4, ash is removed from the fabric filter hoppers with a vacuum system and transported dry to an ash silo. When loaded onto trucks for transport to the disposal site, the ash is wetted with about 20% water (by weight) in order to minimize fugitive dust emissions. Depending upon the specific ash characteristics, this wetting process can result in the release of NH_3 vapors from the ash. Whether or not NH_3 is released from the ash depends primarily on the pH of the aqueous phase on the surface of the ash particles. As the pH increases above a level of 9 to 9.5, there is an increased release of vapor-phase ammonia.

During the test program with urea injection alone, the ammonia concentration in the ash varied over the range of 100 to 200 ppm (measured on a weight basis). The ash ammonia content appeared to be primarily related to the NH_3 slip levels from the SNCR system and, to some extent, the fabric filter cleaning cycles. During long-term testing with the SNCR system alone, and a 10 ppm NH_3 slip limit at the stack, there were no incidents of excessive NH_3 odors during the ash handling process.

Testing has shown that when the SNCR system is operated in conjunction with the dry sodium injection system, the urea injection rate could be increased substantially while maintaining a 10 ppm NH_3 slip level at the stack. This is one of the synergistic benefits of the patented Integrated Dry NO_x/SO_2 Emissions Control System discussed above. However, during these tests, the ammonia concentration in the ash increased to the range of 400 to 700 ppm (weight basis), and there were frequent occurrences of NH_3 odors at the ash silo. Reducing the NH_3 slip set point to the range of 4 to 5 ppm reduced the ammonia concentration of the fly ash down to the 100 to 200 ppm range (weight basis), but the odor problem persisted.

At first, it was thought that the odor problem was a result of the sodium changing the pH of the ash. The pH resulting from placing 0.5 gram of ash in 200 ml of distilled water was 9.3 for an ash sample without sodium injection. The same test run with an ash sample from a test with sodium injection resulted in a pH of 10.3. While the sodium did indeed increase the pH, which in turn would tend to release more NH_3 from the aqueous to the vapor phases, the pH difference did not appear significant enough to account for the ash handling problems encountered.

An interesting observation was made during the pH measurements. While the presence of sodium was found to slightly increase the final pH, it was also found to have a large effect on the rate at which the pH changed as the ash was wetted. Figure 20 shows the change in pH versus time after 0.5 gram of ash is placed into 200 ml of distilled water and stirred. With the coal ash alone, almost 30 minutes are required for the soluble components of the ash to dissolve and change the pH to a final value of 9.3. However, with sodium present in the ash sample, the pH develops almost instantaneously, presumably because of the higher solubility of the sodium compounds in the ash. This more rapid development of the high pH level can result in more rapid and localized release of the ammonia vapor, and may explain the odor problem encountered when concurrently operating the SNCR and sodium systems. Other than decreasing the level of NH_3 slip from the SNCR system, additional approaches to dealing with this issue have not been explored.

CONCLUSIONS

Public Service Company of Colorado, in cooperation with the U.S. Department of Energy and the Electric Power Research Institute, has installed the Integrated Dry NO_x/SO₂ Emissions Control System. The system has been in operation for over three years and preliminary conclusions are as follows:

- NO_x reduction during baseload operation of the unit with low-NO_x burners and overfire air ranges from 63 to 69% with no increase in unburned fly ash carbon or CO emissions.
- With the addition of retractable lances to the SNCR system, improved low load performance of the system urea-based SNCR injection allows an additional 30 to 52% NO_x removal with an ammonia slip limit of 10 ppm at the fabric filter inlet. This increases total system NO_x reduction to greater than 80% at full load, significantly exceeding the project goal of 70%.
- The ability to follow the temperature window by rotating the ARIL lances has been demonstrated and also proved to be an important feature in optimizing the performance of the SNCR system.
- SO₂ removal with calcium-based dry sorbent injection into the boiler at approximately 1000°F flue gas temperature was disappointing with less than 10% removal achieved.
- SO₂ removal with calcium-based dry sorbent injection into the fabric filter duct has been less than expected with a maximum short term removal rate approaching 40%.
- Sodium bicarbonate injection before the air heater has been very effective with short term SO₂ removals of over 80% possible. Longer term testing has demonstrated removal near 70% at an approximate NSR of 1.0.
- Sodium sesquicarbonate injection ahead of the fabric filter can achieve 70% removal on a long term basis, at an approximate NSR of 2.0.
- NO₂ emissions are generally higher when using sodium bicarbonate than when using sodium sesquicarbonate. The NO₂ generated during sodium-based injection is related to SO₂ removal and the cleaning cycle of the fabric filter, but all factors important to NO₂ generation are not fully understood.⁽¹¹⁾
- Long term testing of the integrated system demonstrated the synergistic benefit of operation with SNCR and sodium-based dry sorbent injection (i.e., reduce NO₂ and NH₃ emissions).
- When the SNCR and dry sodium systems were operated concurrently, an NH₃ odor problem was encountered in the area around the unit 4 ash silo. This problem appears to be related to the rapid change in pH due to the presence of sodium in the ash.

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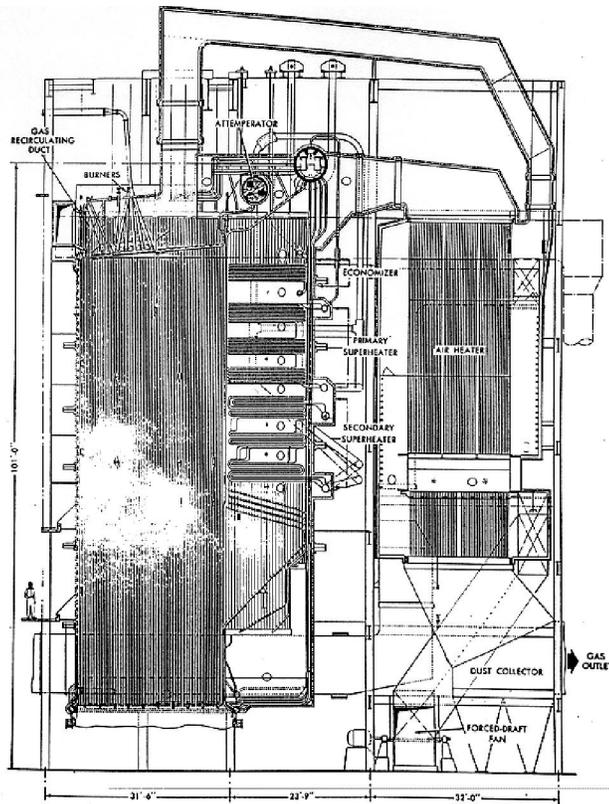


Figure 1. Boiler Elevation

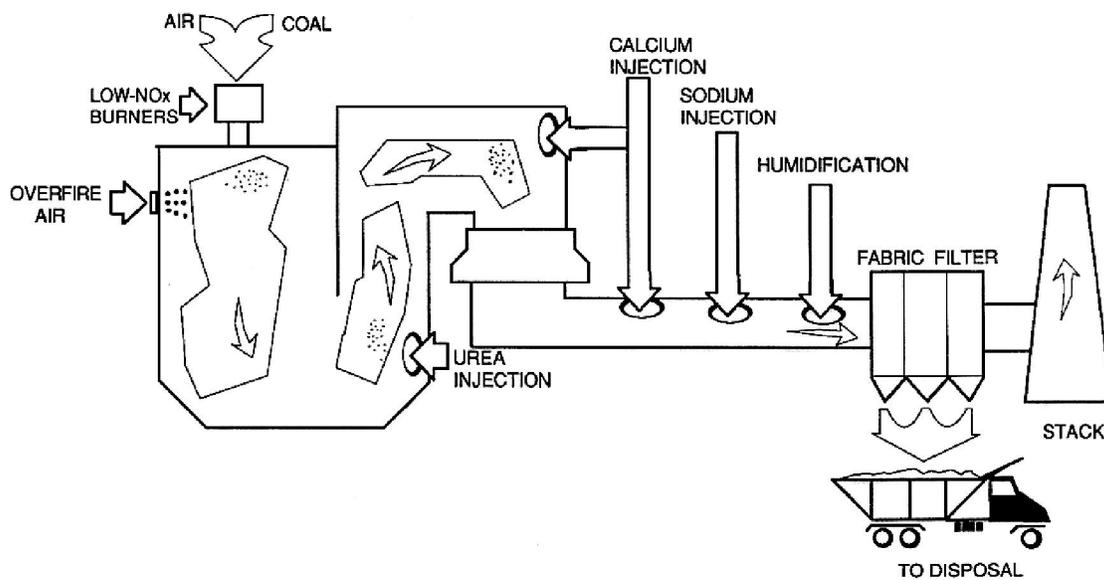


Figure 2. Process Flow Diagram of the Integrated NO_x/SO_2 Emission Control System

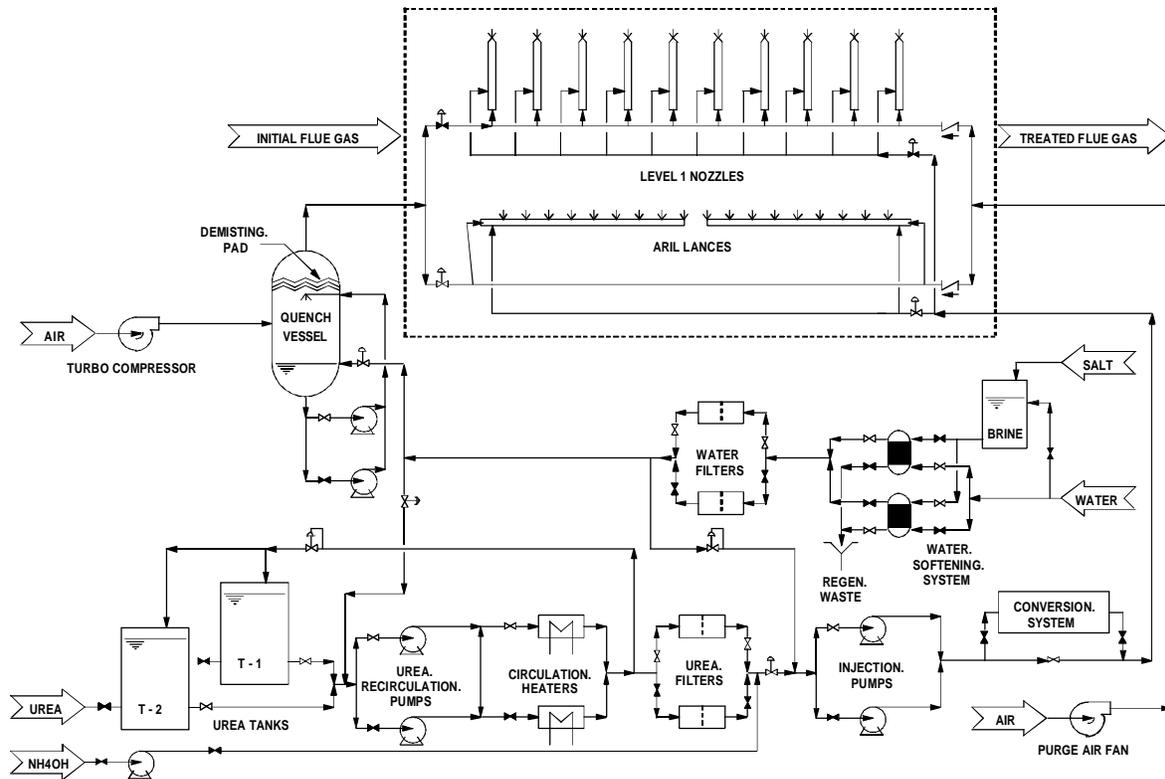


Figure 3. SNCR System Flow Diagram

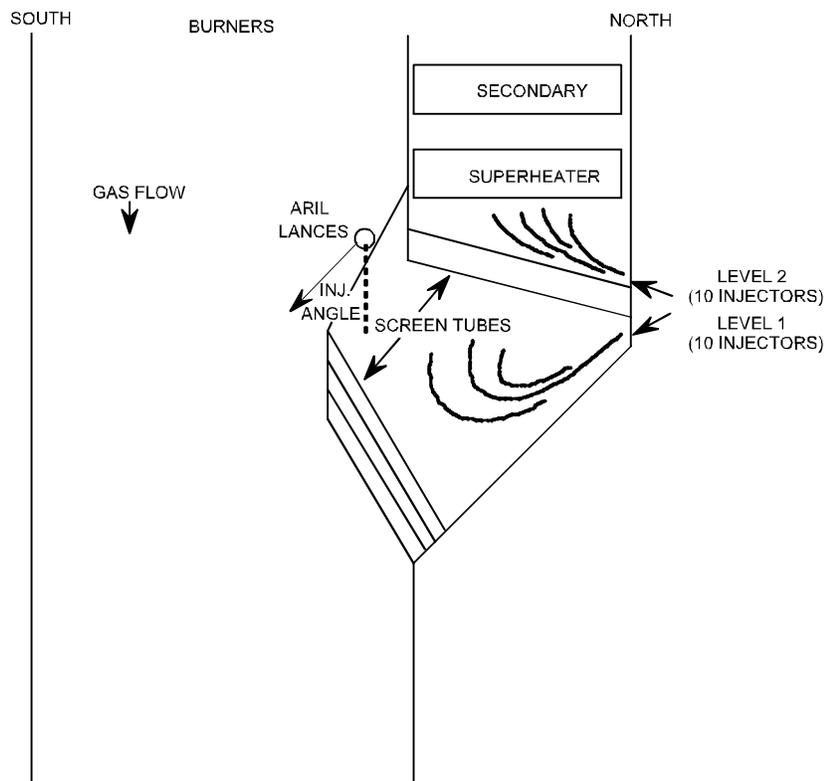


Figure 4. SNCR Injection Locations

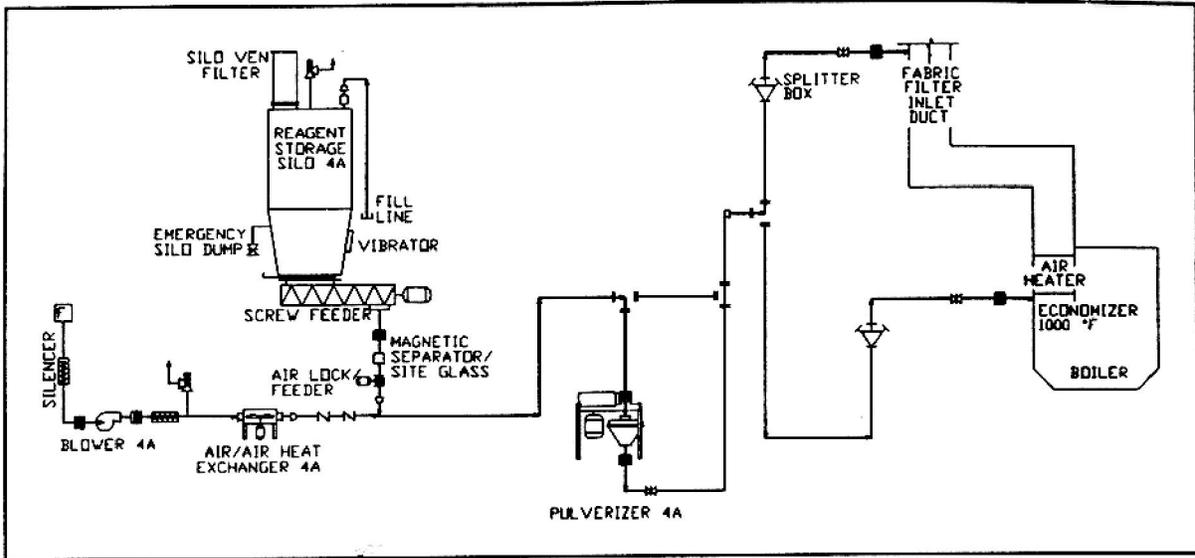


Figure 5. Dry Sorbent Injection Flow Diagram

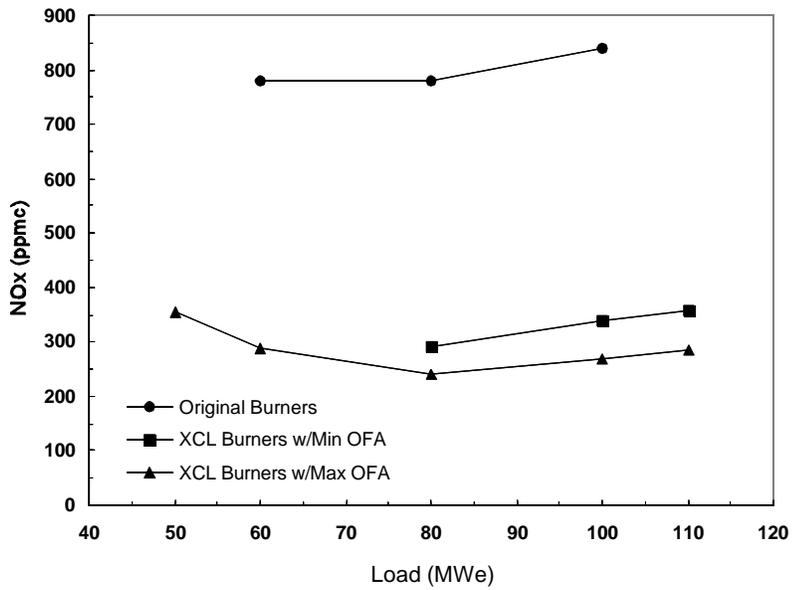


Figure 6. NO_x Emissions Before and After Low-NO_x Combustion System Retrofit

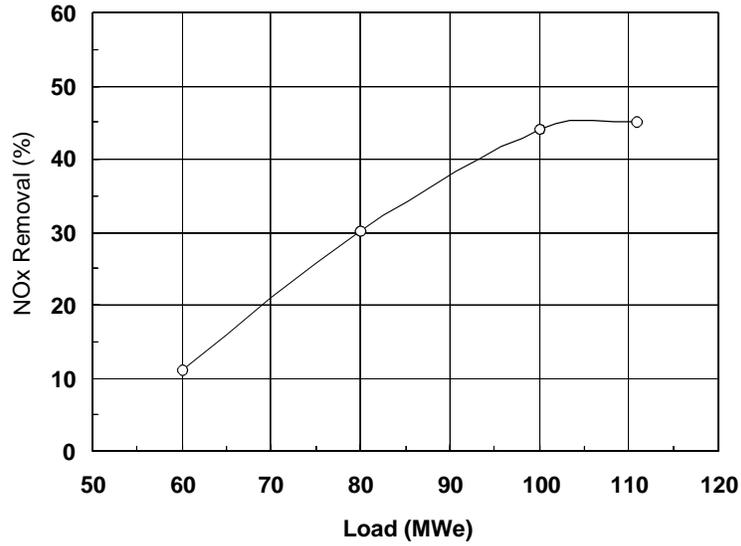


Figure 7. Performance of the Original SNCR System as a Function of Load (10 ppm NH₃ slip limit)

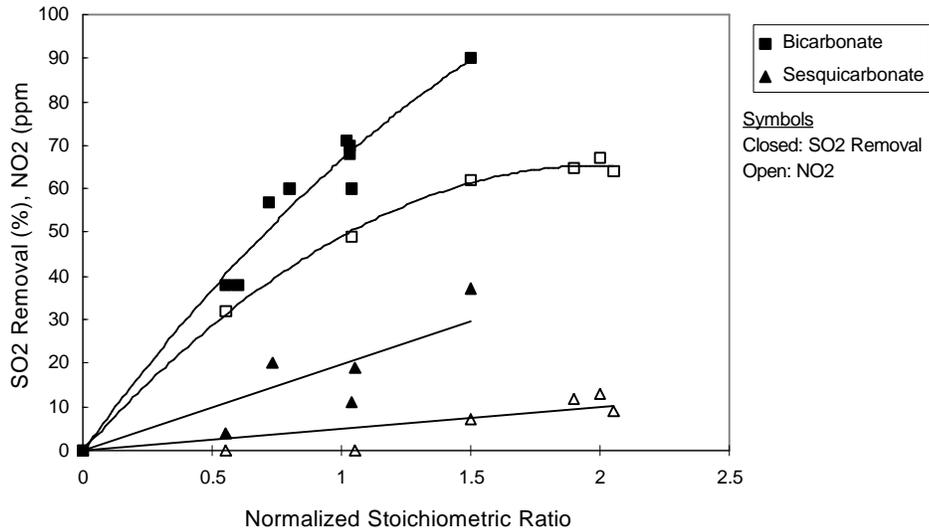
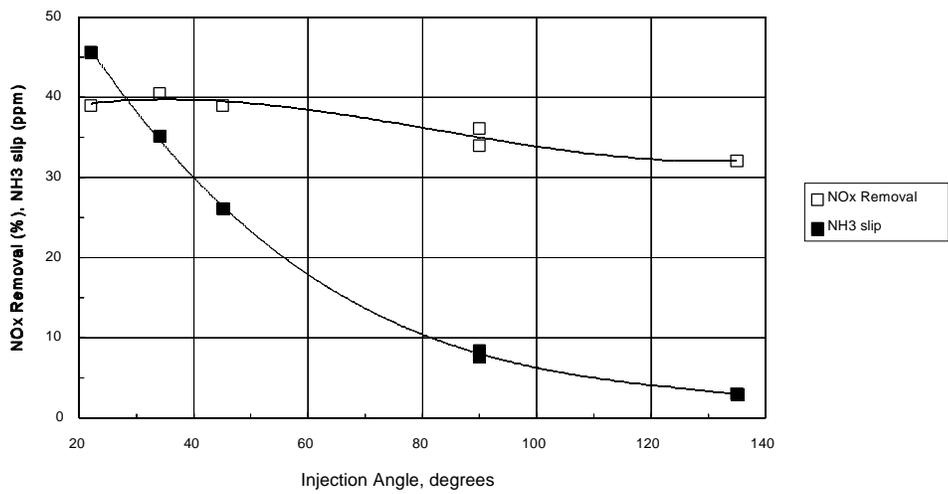
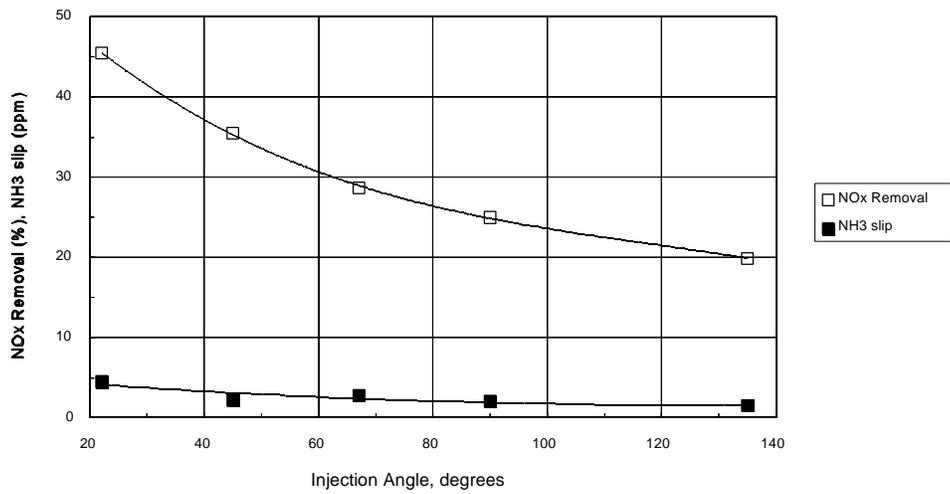


Figure 8. Performance of Sodium Dry Sorbent Injection (sodium sesquicarbonate injected ahead of the fabric filter; sodium bicarbonate injected ahead of the air preheater)

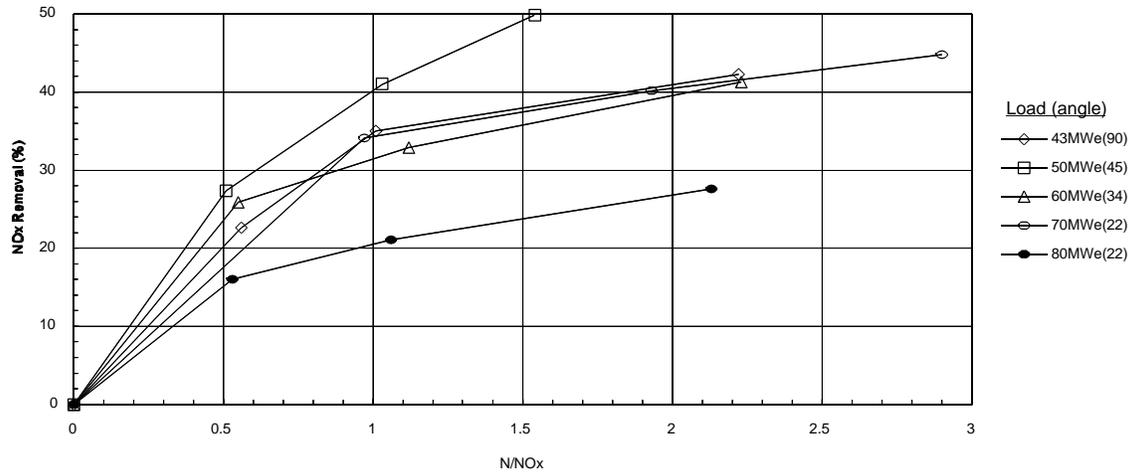


(a) 43 MWe

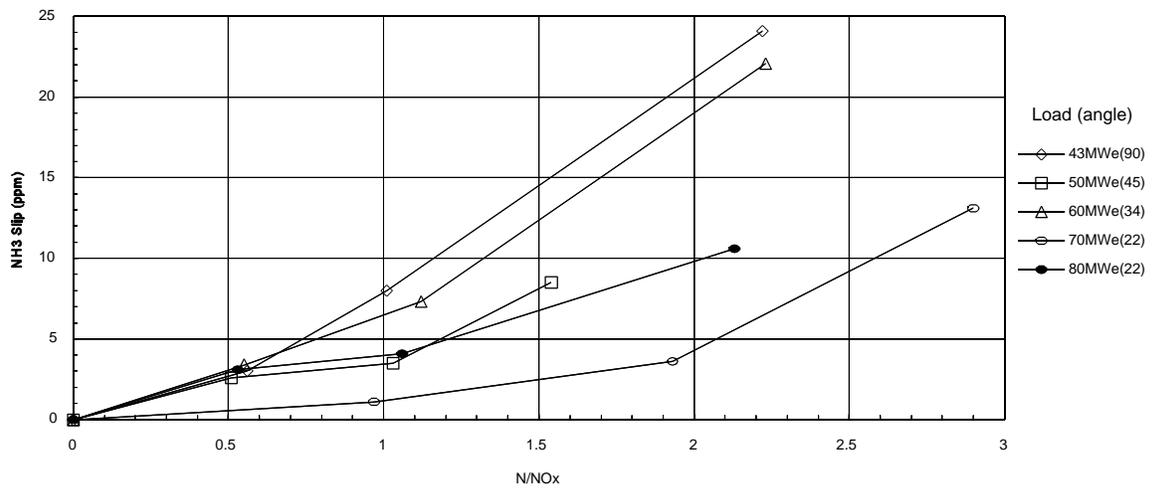


(b) 50 MWe

Figure 9. Effect of Injection Angle on NO_x Removal and NH₃ Slip
(Loads: 43 and 50 MWe, N/NO_x = 1.0)



(a) NOx Removal



(b) NH3 slip

Figure 10. ARIL Lance Performance Over the Load Range: 43 to 80 MWe

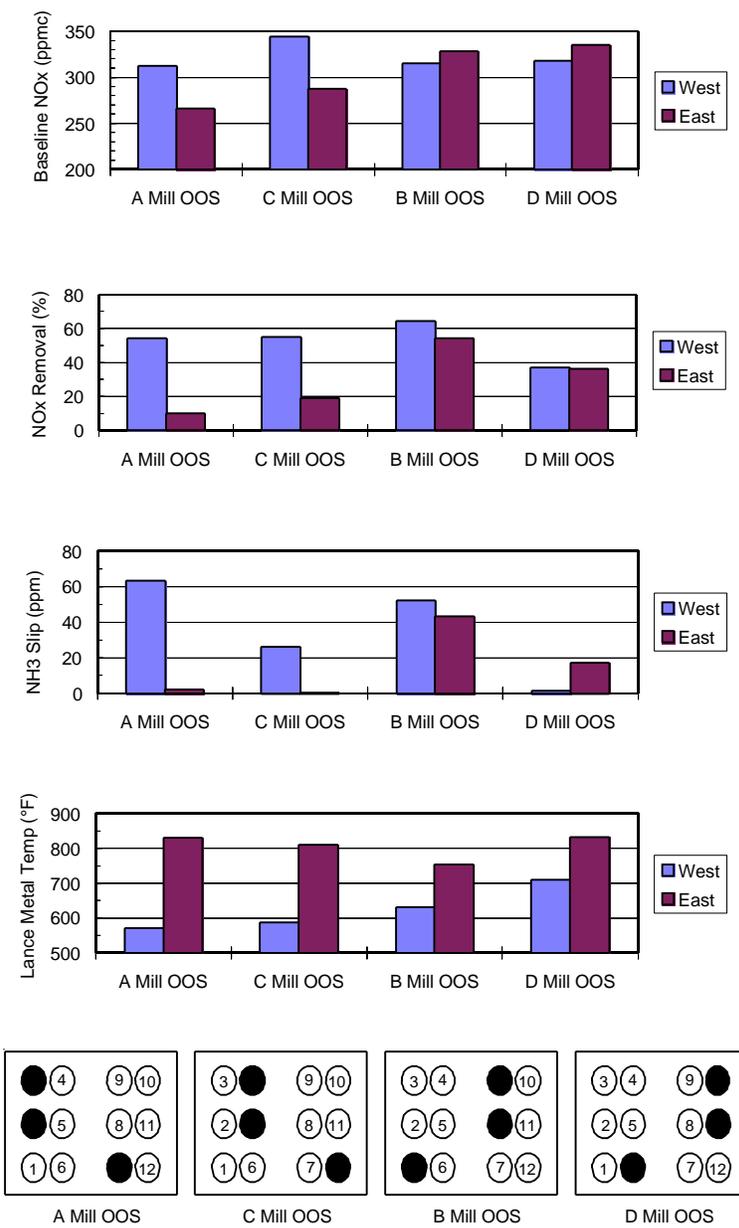


Figure 11. East-West Baseline NO_x Emissions, NO_x Removals, NH₃ Slip Levels and Lance Metal Temperature Distributions as a Function of Mill-in-Service Pattern at 60 MWe (N/NO_x = 2.0, 22° Injection Angle)

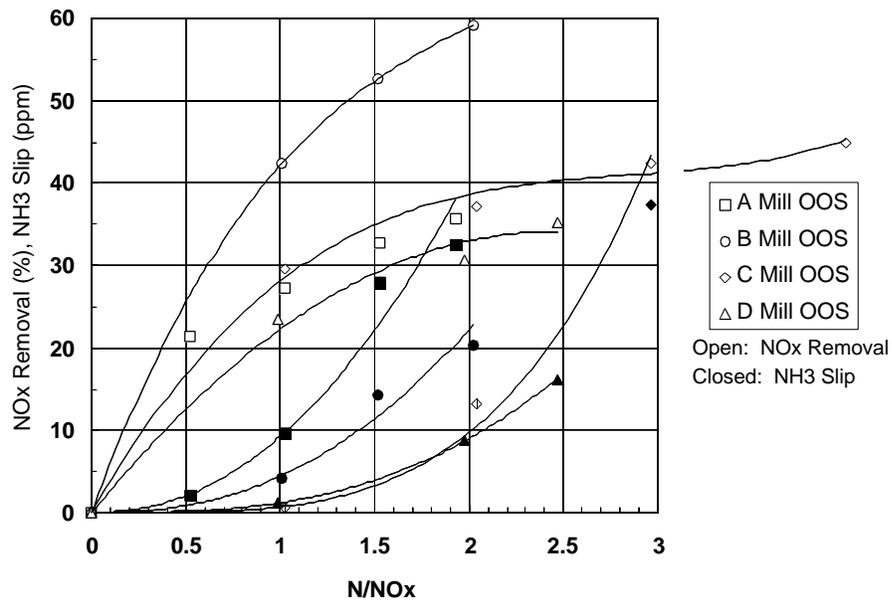


Figure 12. Effect of Mill-in-Service Pattern on ARIL Lance Performance at 60 MWe (22° Injection Angle)

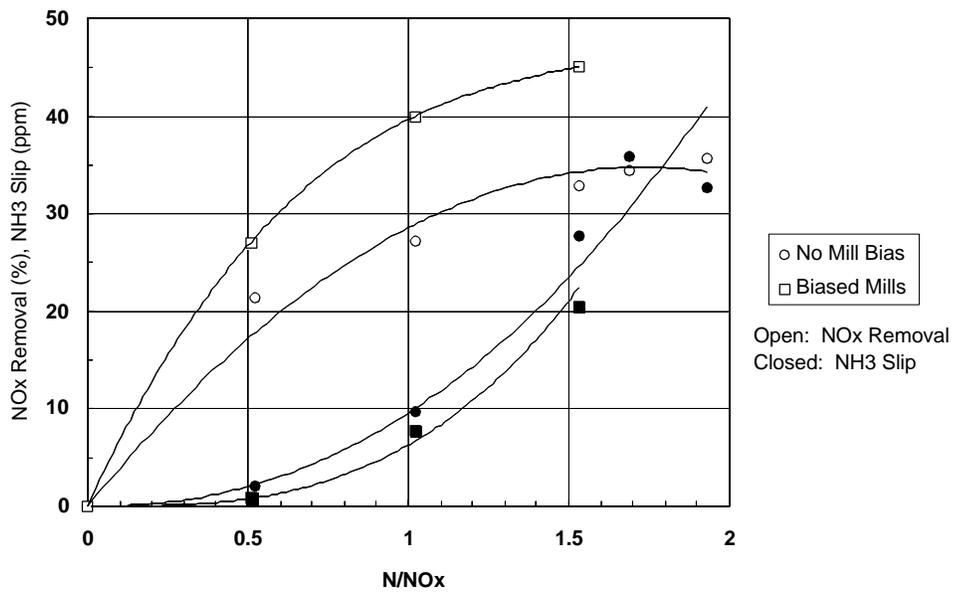


Figure 13. Effect of Coal Mill Bias on ARIL Lance Performance at 60 MWe (A Mill OOS, 22° Injection Angle)

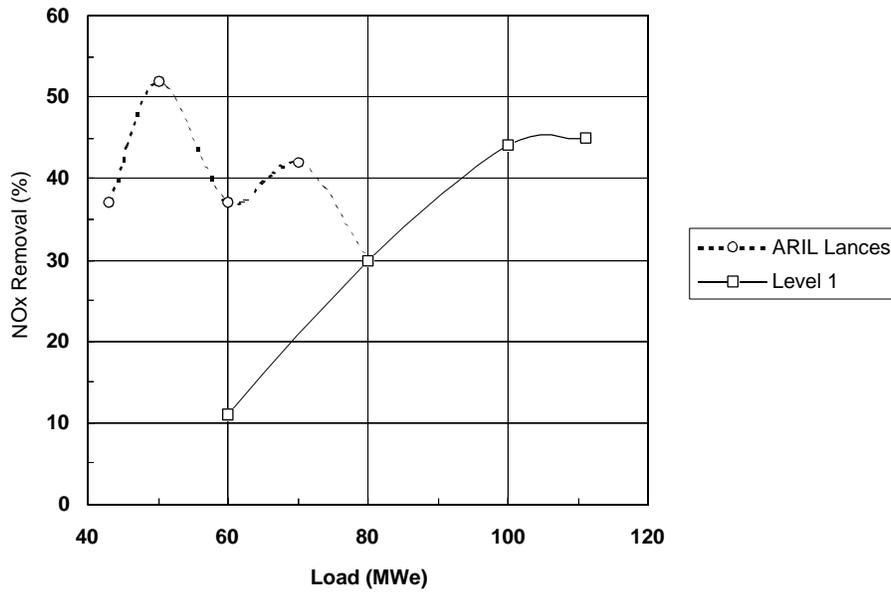


Figure 14. NO_x Removal as a Function of Load for an NH₃ Slip Limit of 10 ppm

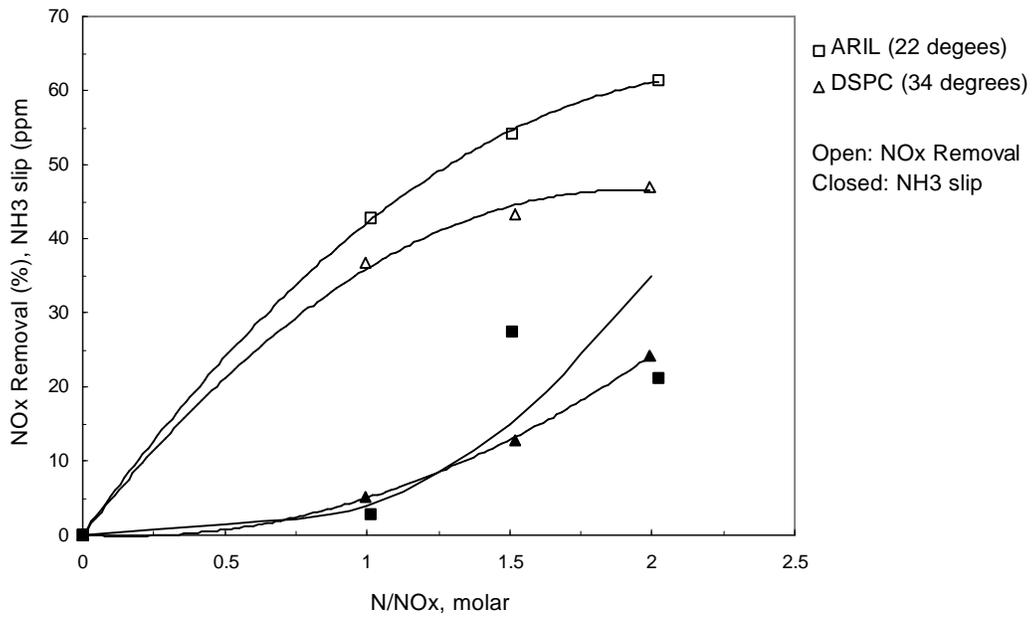


Figure 15. Comparison of the ARIL and DPSC Lance Performance

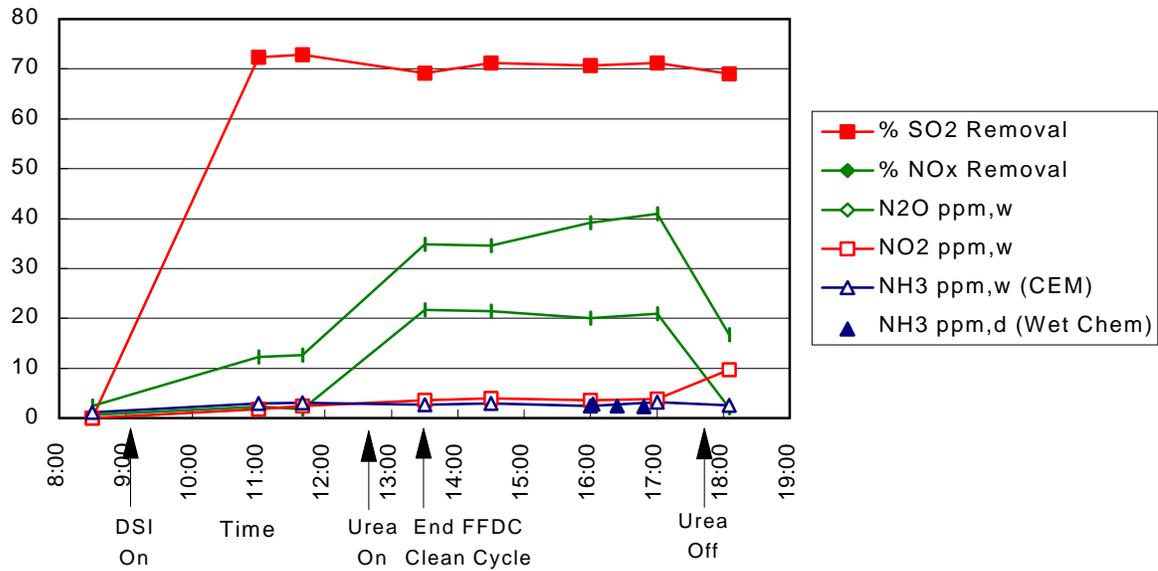


Figure 16. Time History of 100 MWe Integrated Test with Sodium Sesquicarbonate Injection ($2Na/S = 2.0$, $N/NO_x = 0.6$, A Mill OOS)

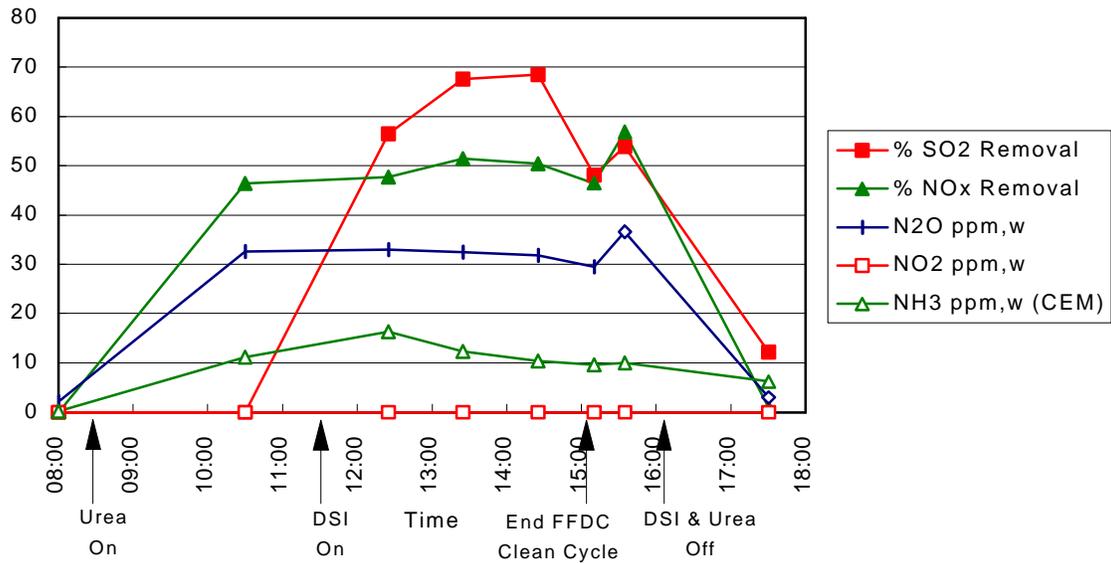


Figure 17. Time History of Integrated Test with Sodium Bicarbonate Injection ($2Na/S = 1.1$, $N/NO_x = 1.1$, 100 MWe, 4 Mills in Service)

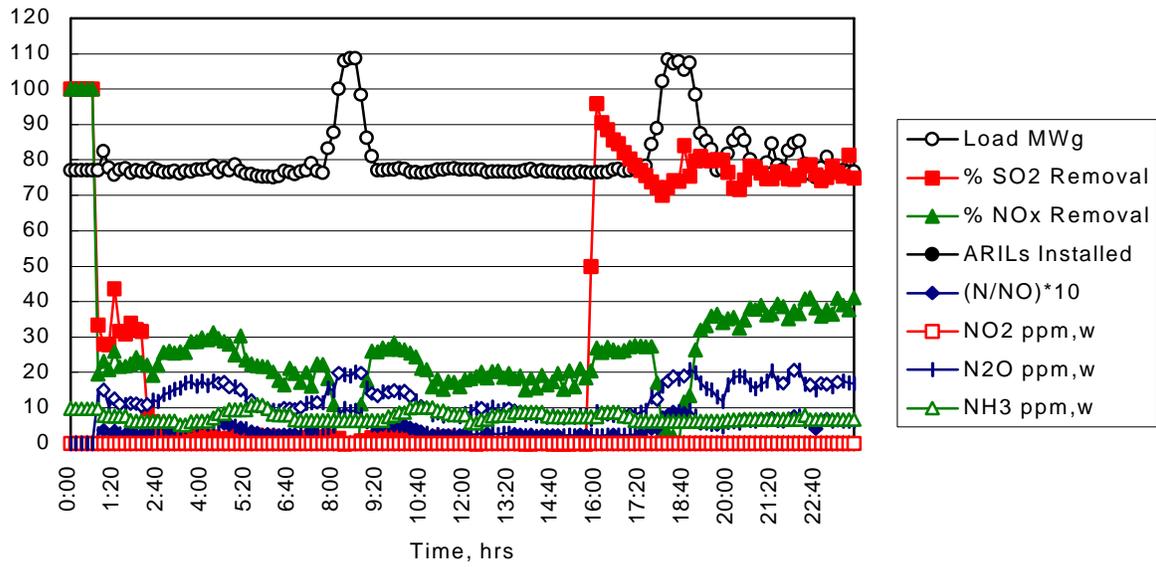


Figure 18. Long-Term Integrated Load-Following Test Results (February 29, 1996)

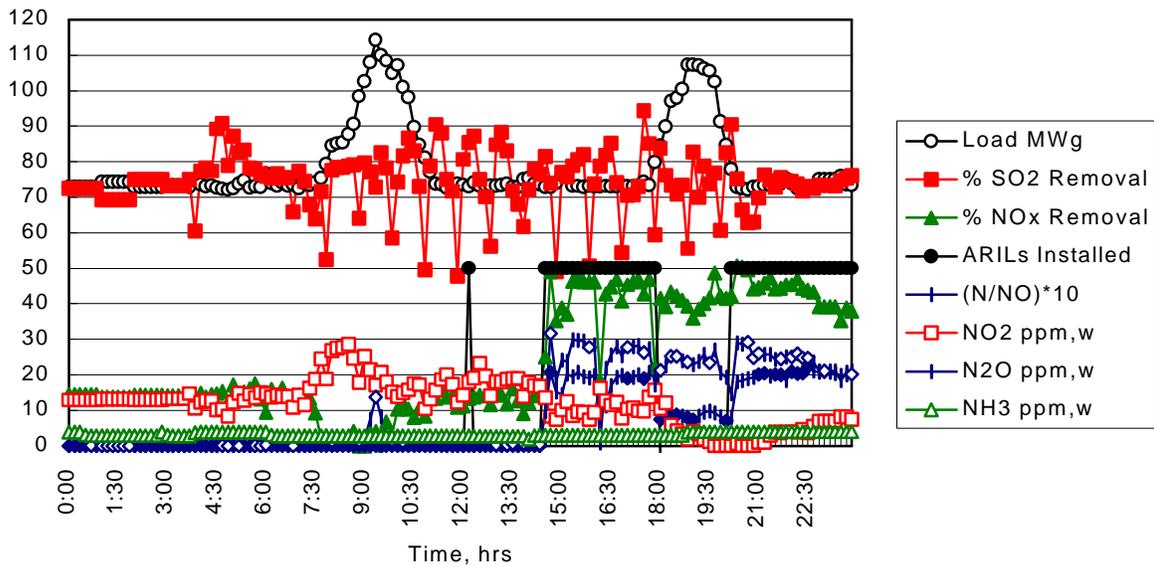


Figure 19. Long-Term Integrated Load Following Test Results (March 4, 1996)

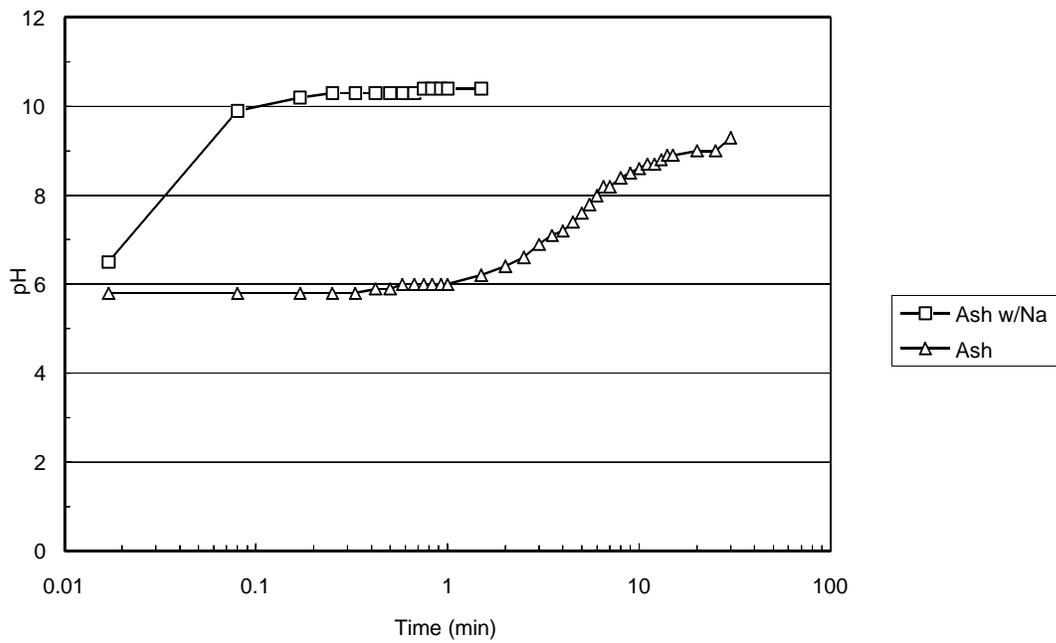


Figure 20. pH versus Time for Coal Ash and Coal Ash/Sodium Mixture (0.5 grams of ash in 200 ml of H₂O)